# Temporal analysis of light-curves from transient sources

## Evaluation of experimental delays from detectors TOAs lists

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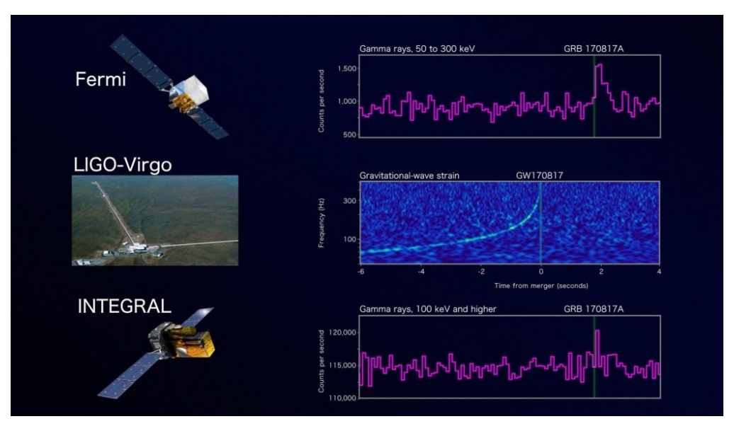
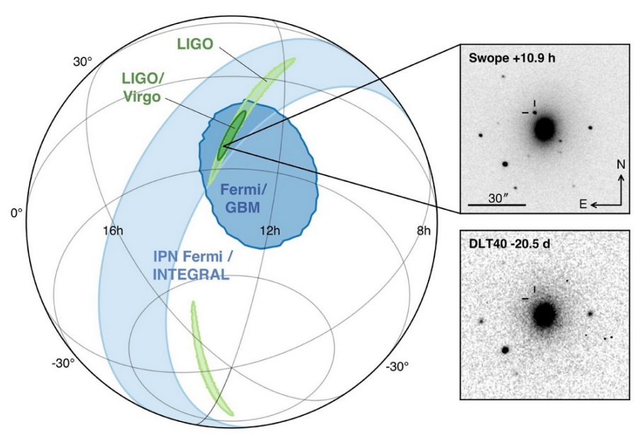
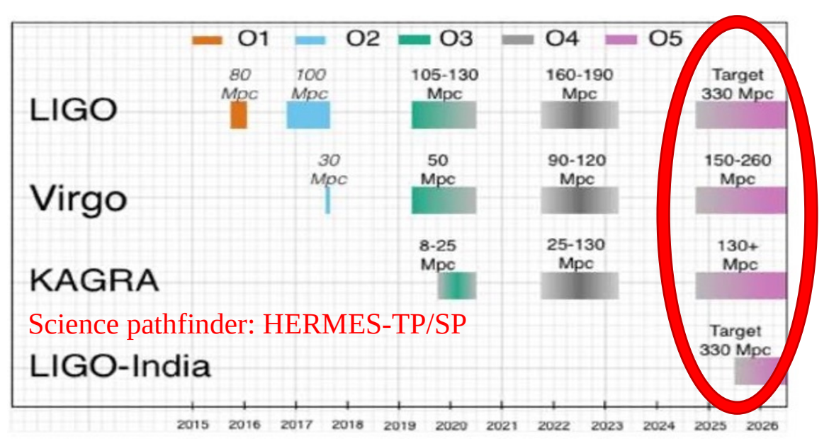
## Introduction

Gamma-Ray-Bursts (GRBs) are short, intense and unrepeatable flashes of radiation generated by the collapse of a Massive star or the collision of two Neutron Stars (NSs) in an NS-NS binary system. On the 17th of August 2018, the first joint detection of a Gravitational Wave (GW) signal and its electromagnetic counterpart (a short GRB) gave birth to “Multi-messenger Astrophysics.” Different signals carry different information that can be combined to answer unsolved questions in the physical and astrophysical realms. The described case is, until now, the only joint detection ever observed.



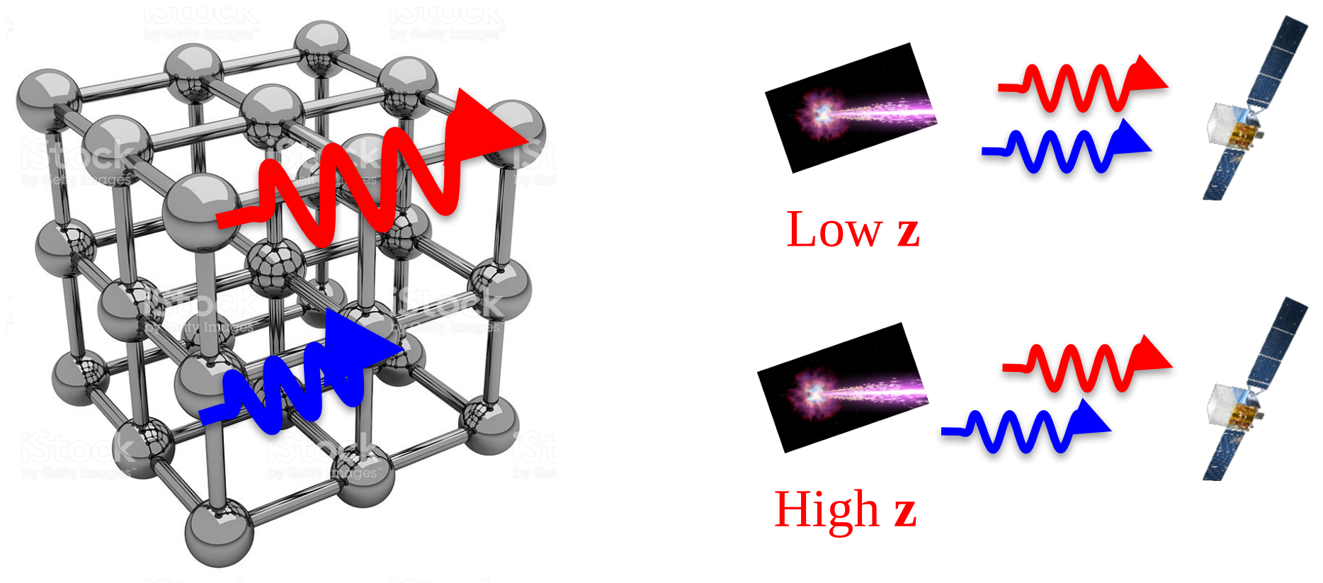


Source localization obtained by LIGO/Virgo and the Fermi/Integral and Fermi/GBM instruments.



HERMES mission operability related to the O5 run of GW intererometer

Detecting and localizing every transient event is crucial to maximizing the possibility of joint detection observations. The HERMES mission aims to obtain all-sky coverage in the high energy band by launching into orbit a nano-satellite constellation. Knowing GRB observation delays between in-orbit distributed detectors makes it possible to localize transient sources using the triangulation method.



High energy wavelenght (blue) are diffused more than lower energy (red)

**MP or LIV predictions:**

$|v_{phot}/c - 1| \approx \xi\,[E_{phot}/(M_{QG}\,c^2)]^n$

$\xi \approx 1$

n = 1,2 (first or second order corrections)

$M_{QG} = \zeta\, m_{PLANCK} \quad (\zeta \approx 1)$

$m_{PLANCK} = (hc/2\pi G)^{1/2} = 21.8\ 10^{-6}\,g$

Implications for travel time of photons:

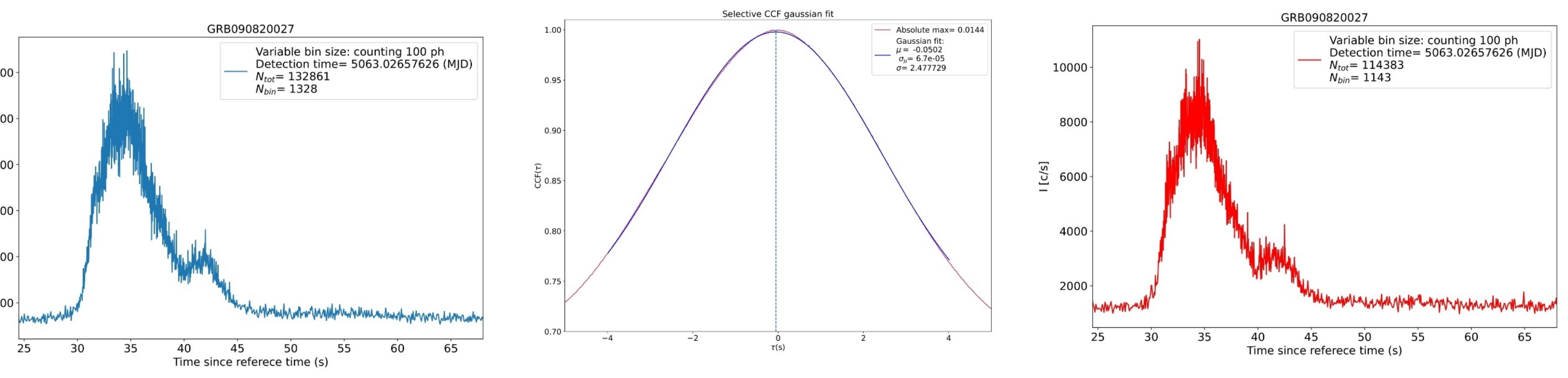
$$\Delta t_{MP/LIV} = \xi\,(D_{TRAV}/c)\,[\Delta E_{phot}/(M_{QG}\,c^2)]^n$$

$$D_{TRAV}(z) = (c/H_0)\int_0^z d\beta\,(1+\beta)/[\Omega_\Lambda + (1+\beta)^3\,\Omega_M]^{1/2}$$

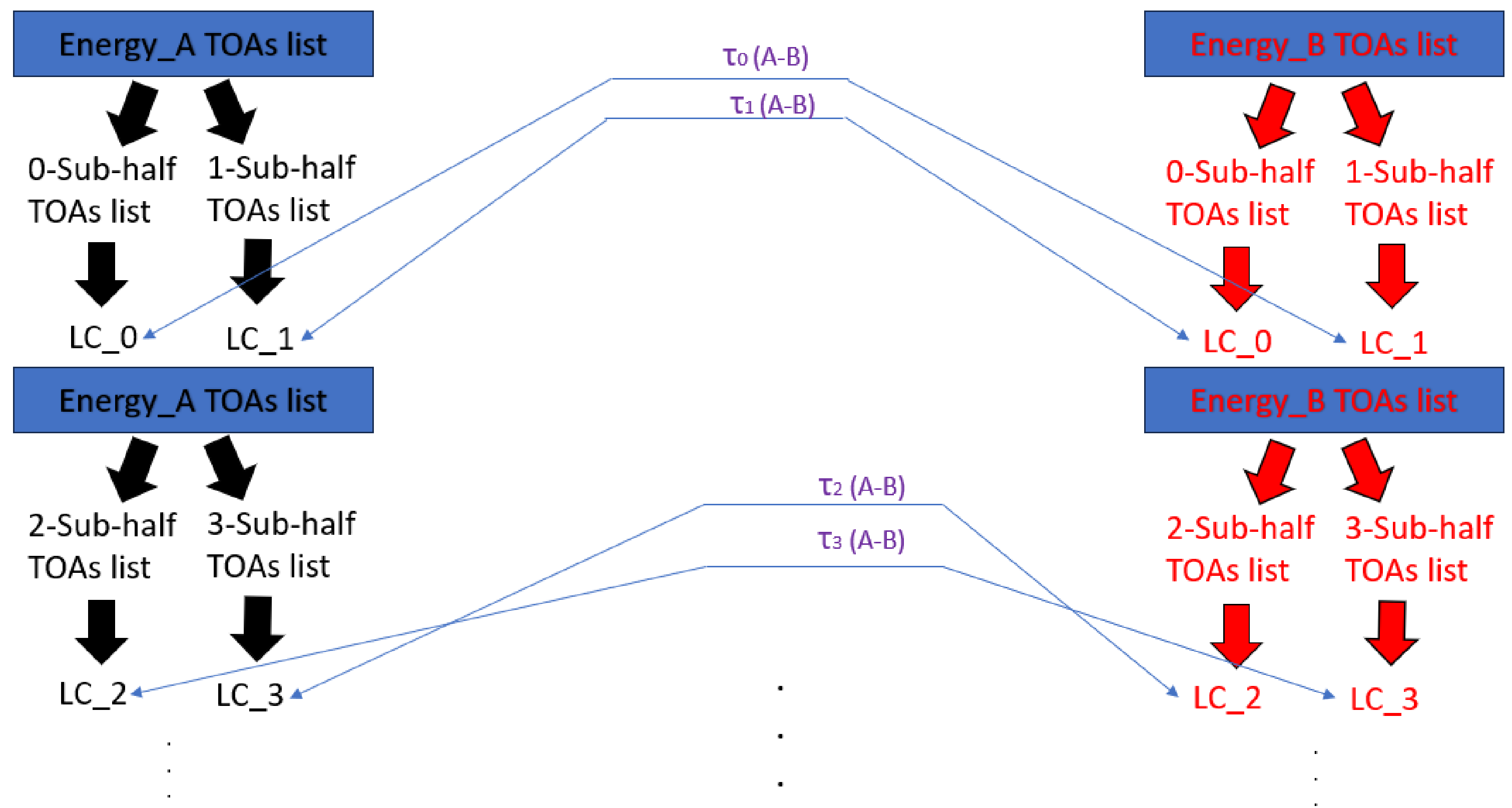
The estimation of delays is obtained through innovative temporal analysis techniques. These can be applied to a sample of GRBs to place constraints in the realm of quantum gravity. Considering the typical energy band ( KeV – TeV ), delays due to vacuum dispersion effects would be amplified by cosmological redshift. We assume that delays due to emission mechanisms are constant for each. Studying the trend of delays between light curves in different energy bands allows for verifying the existence or absence of potential first-order quantum gravity effects.

## Methodology

The Cross-correlation function (CCF) is a mathematical operation that quantifies the grade of similarity between two signals. A single estimate of the theoretical delay between signals only if we have knowledge of the theoretical signals associated with sources (***Leone,2024a***).
Each detector observation corresponds to a specific Poissonian realization of the electromagnetic signal interacting with the detector material. Due to the quantum measurement process, each realization is linked to a distinct Poissonian footprint, referred to as the "**quantum fingerprint**“ (Leone, 2024b).
Let’s consider two GRB light curves of two identical Fermi/GBM detectors (NaI) observing the same source in the same spatial position under the same conditions. The delay between the two observed light curves is -0.05 s!



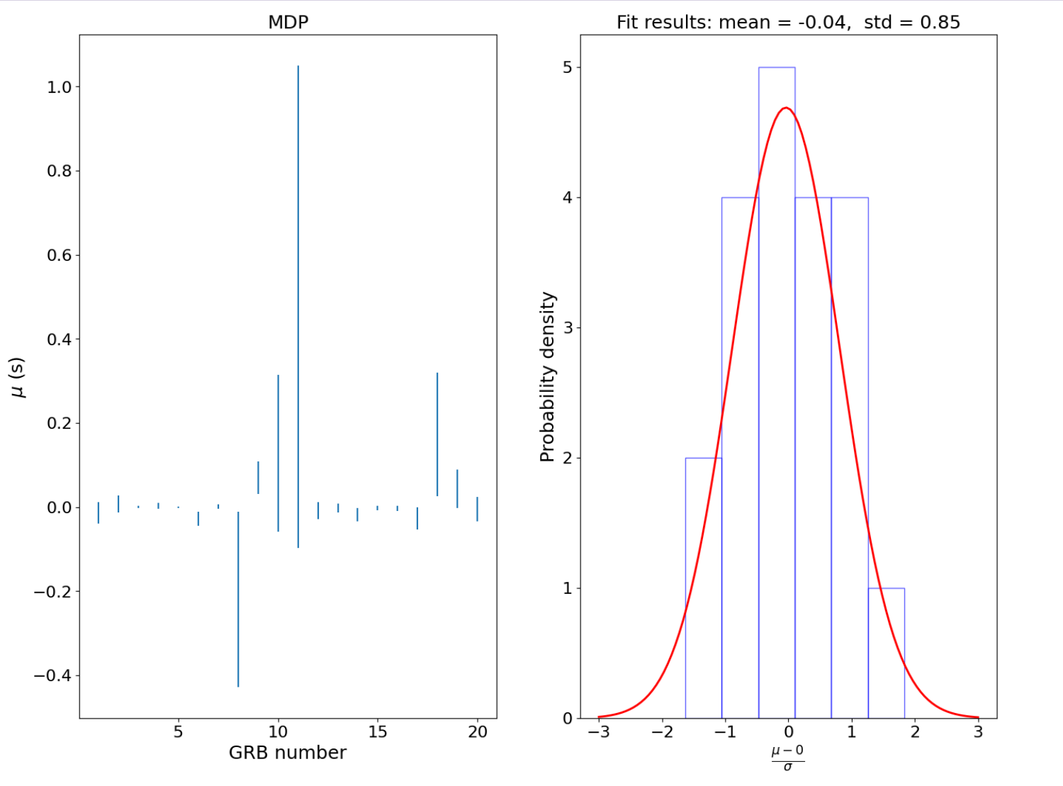
That is due to the quantum variability related to these experimental observation. If we had 100 GBM detectors at our disposal, the distribution of delays would be centered around zero delay. We do not have 100 GBM detectors or 100 detectors in different bands observing the same source. The only way to obtain a correct statistical delay is by conducting numerous simulated experiments. The Modified Double Pool (MDP) method described in ***Leone, 2024b*** allows us to estimate the closest experimental delay to the true theoretical delay between two signals of any kind.



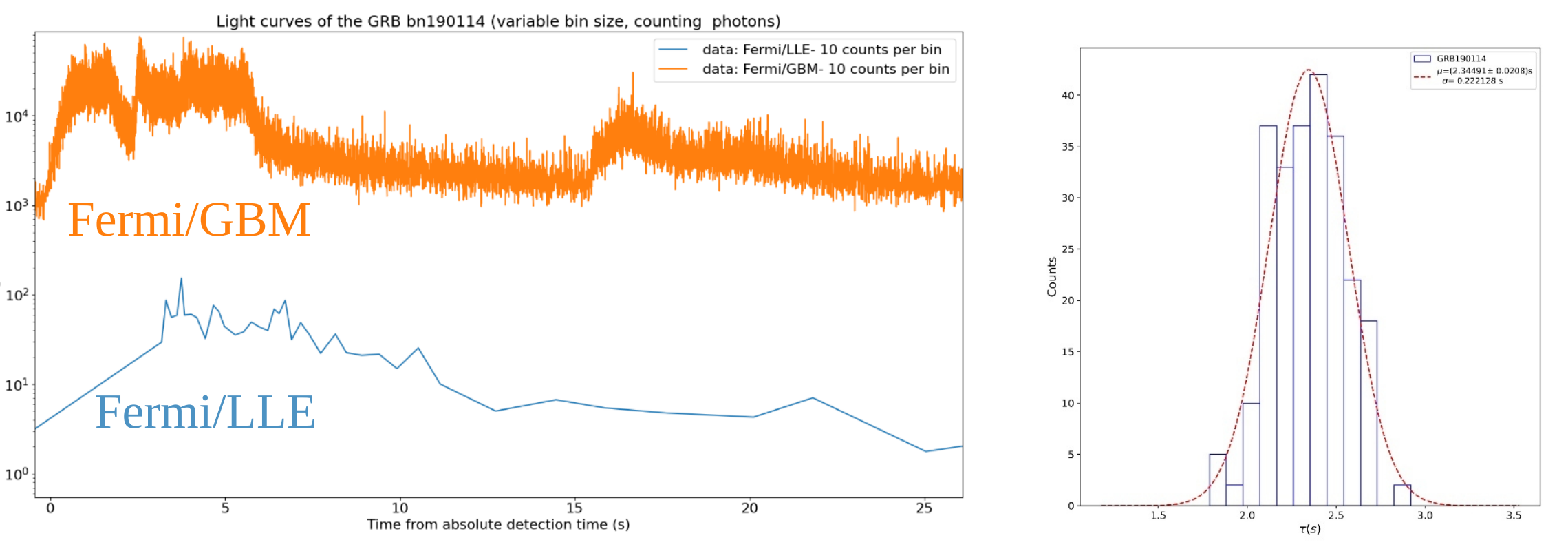
We have at our disposal two starting lists of Time of Arrivals obtained by any detectors in different energy bands or different spatial position (but same energy bands). Two sub-lists of ToAs are produced with a random division from the two starting lists of TOAs. By this way, two couples of light curves are generated and cross-correlated to obtain two delays as shown in figure. Once the delays are obtained, the two lists are deleted, and two new random divisions are performed to obtain two new pairs of light curves, allowing the estimation of two other delays. This procedure is repeated n/2 times until n delays are obtained, leading to a distribution that is centered into the best achievable delay with a certain standard deviation.

## Results

- To demonstrate the effectiveness of the MDP method we consider a sample of 20 GRBs as observed by HERMES detectors (~50 〖cm〗 ^2).
- For each GRBs, two different detectors are considered.
- Due to the quantum measurement process of detectors, two different detectors’ light curves can be associated to a significative delay.
- The MDP method is applied to each GRB detector couple, to verify the experimental delay between them.
- The distribution shows how the method can estimate the closest statistical delay to the true expected theoretical delay (zero delay).

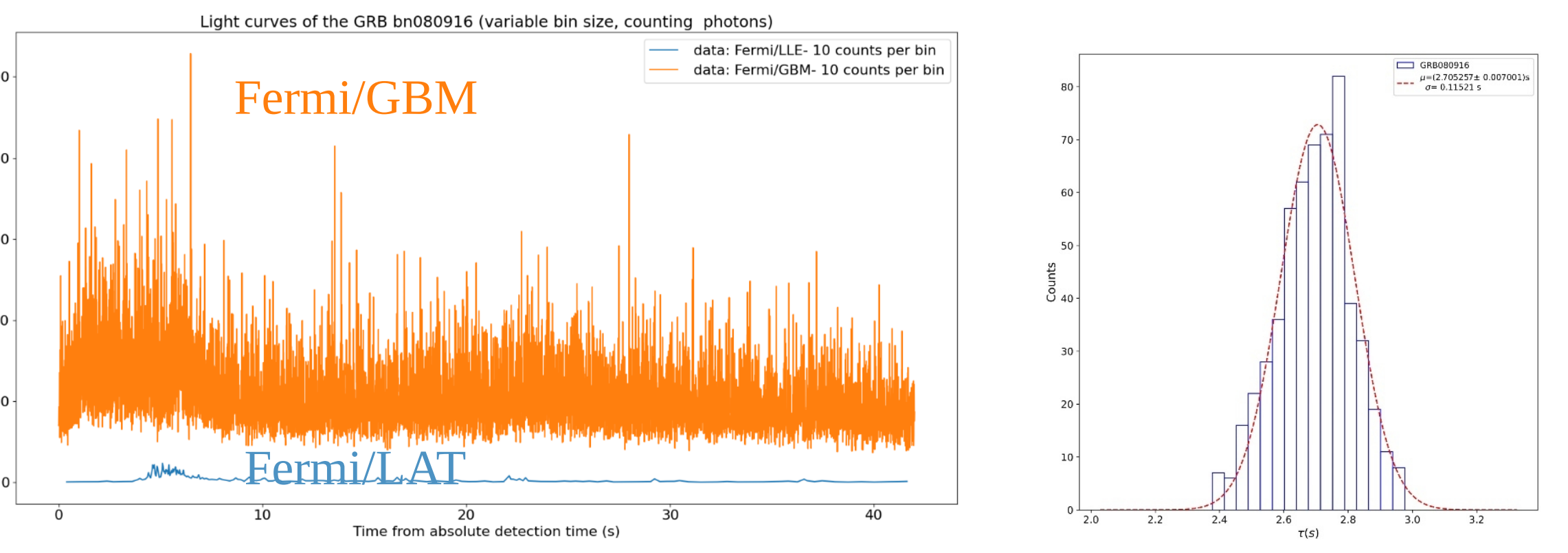


demonstrate Figure 1: The eft plot shows the delays estimated between couples of detectors that observe the same GRB with the associated error. Right plot shows the Gaussian distribution of residual in unit of standard deviation.



1 KeV – 1 MeV
10 MeV – 100 GeV

z=0.4245
μ = 2.34 ± 0.022



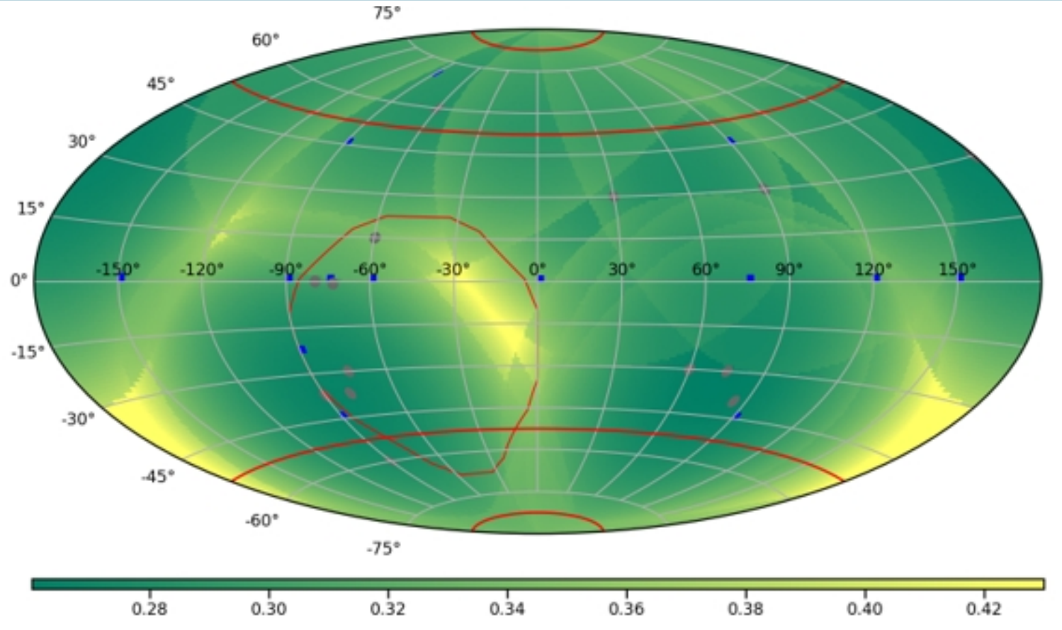
1 KeV – 1 MeV
30 MeV – 300 GeV

z=4.35
μ = 2.7 ± 0.11

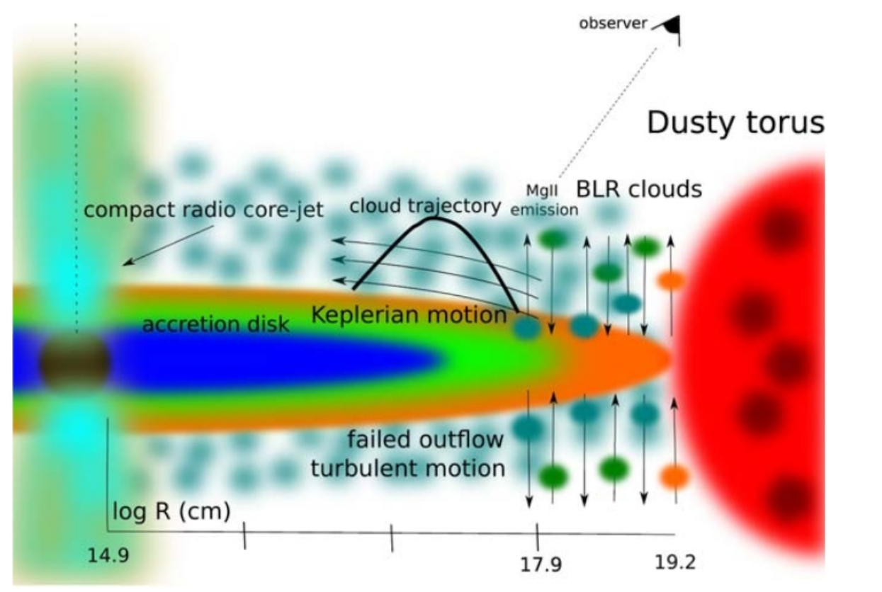
## CONCLUSION (HERMES launch, further applications of the method)

Planned launch in february 2025

- HERMES (High Energy Rapid Modular Ensemble of Satellites) 6 units:
  - HERMES-SP (High Energy Rapid Modular Ensemble of Satellites - Scientific Pathfinder) funded by EC under the H2020 programme
  - HERMES-TP (HERMES Technology Pathfinder) funded by ASI



Continuos All-sky configuration for 15 satellites (in blue) and the associated pointing (grey), 8 LEO nano-sats, 7 SSO nano-sats.



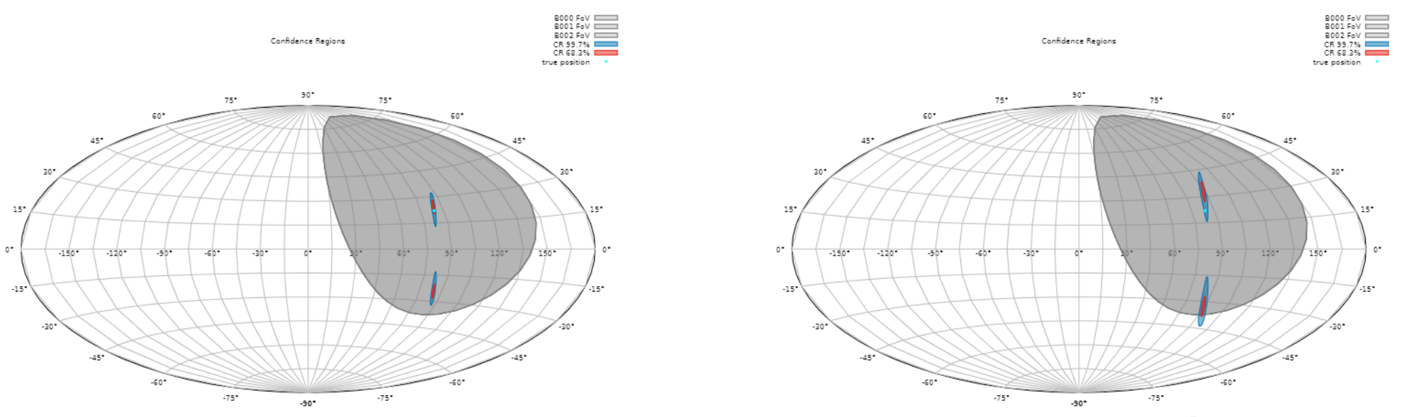
Michal Zajaček et al., 2020

- Probing both the spatial extent and the internal architecture of the broad-line region (BLR).
- **Time delay between the variations in a selected emission line and those in the continuum emission**.
- Employing the fundamental concept of light travel time in the propagation of radiation, it is possible to derive the characteristic size of the BLR.

**Accuracy in determining α and δ with $N_{SATELLITES}$:**

$$\sigma_\alpha \approx \sigma_\delta = c\,\sigma_{ToA}/\langle baseline\rangle \times (N_{IND} - N_{PAR} + 1)^{-1/2}$$

Simulation of the CRAB Pulsar localization with HERMES-SP detectors (***Leone, 2024c***).



Baseline= 4600 Km

The developed method offers the possibility to manage with experimental lists of ToAs, results of the quantum measurment process of detectors. Despite the Poissonian nature of the observations, the method provides a **statistical delay** that is closest to the theoretical signal delay. The associated error is the standard deviation of the obtained standard deviation, that reflect the observations’ true statistics.
Figure 1 is consistently narrowed to zero, showing that it is possible to go beyond the quantum nature of detectors obtaining the expected theoretical delay.
The residual distribution is associated with standard deviation of 0.85: this depend on the sample of GRBs used and the considered effective area (A~50 . The precision of the method increases, as the and depends on the GRB quality. That quality refers to the temporal structure of the GRB and the GRB brightness (see, e.g., Sanna et al. 2020, Thomas et al. 2023, Burgess et al. 2018, G. Ghirlanda, ... W. Leone et al., 2024).
Applications are meant to be found in several astrophysical fields, such as the transient events localization via triangulation method, AGN reverberation mapping or the investigation of quantum gravity effect (searching for first or second-order costrains in LIV models).

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